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An 8500-year palynological record of vegetation, climate change and human activity in the Bosten Lake region of Northwest China

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ABSTRACT

Palynological dataset for the XBWu-46 sediment core extracted from Bosten Lake at the south-eastern end of the Tian Shan, Northwest China, contains a climate record divided into three major intervals: a period of increasing aridity (ca. 8540–4000 cal. yr BP), a peak arid phase (ca. 4000 to 2000/1500 cal. yr BP), and an interval of increasing humidity towards the core top (ca. 60 cal. yr BP). Correlation with other climate proxies from different regions implies that hydrological conditions in Northwest China were governed by Asian summer monsoon precipitation during the early and middle Holocene and that the increase in humidity over the last two millennia was controlled by westerly-derived precipitation. Regional evidence for early human activities in the lake sediments starts to accumulate from the onset of the driest interval comprising records of enhanced charred grass fragment concentrations (since ca. 4350 cal. yr BP), and pollen of *Cerealia* type (since ca. 4000 cal. yr BP), *Xanthium* (since ca. 3700 cal. yr BP), and *Cannabis* type (since ca. 2500 cal. yr BP). These signals are likely related to early agro-pastoral populations of regional Andronovo Culture that, according to archaeological data, appeared in the south-eastern Tian Shan around 4000 cal. yr BP. In addition, increased *Xanthium* pollen and charred grass fragment abundances point to enhanced human impact linked to intensified Silk Road activities during the Han dynasty (206 BCE–220 CE).

1. Introduction

Bosten Lake (also known as Bosten Hu) is the largest natural freshwater lake of the Xinjiang Uygur Autonomous Region in Northwest China. It is situated in the eastern Tian Shan at the northern rim of the Tarim Basin occupied by the vast Taklamakan Desert (Fig. 1). Hyper-arid conditions in most parts of the Xinjiang region are caused by its position in the rain shadow of the high Central Asian mountains, which block moisture transport from the Atlantic Ocean (Aizen et al., 2001; Domrös and Peng, 1988). In the middle Holocene the study area was supposedly influenced by a stronger-than-present Asian summer monsoon (Chen et al., 2006a; X. Feng et al., 2006; Kleinen et al., 2011; Morrill et al., 2003; Rudaya et al., 2009).

The major water inflow to Bosten Lake is provided by the Kaidu River (Kaidu He), which originates in the Tian Shan and sensitively reacts on changes in the atmospheric precipitation and melt water supply (Li et al., 2003). The overall scarcity of long and continuous records from the entire Northwest China region means that the Bosten Lake sediments represent a unique archive for documenting Holocene changes in vegetation and climate within the lake catchment area (Chen et al., 2006a, 2006b; Huang et al., 2009; Mischke and Wünnemann, 2006; Wünnemann et al., 2006; Zhang et al., 2009). These studies, mainly focusing on chronological problems, lake catchment geomorphology, and sediment geochemistry, revealed sequential intervals of changes referring to the regional climate, river inflow, lake water depth, salinity, and temperature; however, some of these published environmental interpretations remain inconclusive or contradictory, e.g., those concerning salinity changes (Zhang et al., 2009). The challenging fact that various proxies inscribed in the lake sediments apparently record contrasting palaeoenvironmental signals can be partly explained by the topographic and environmental variability within the relatively large catchment area. Accordingly, different data

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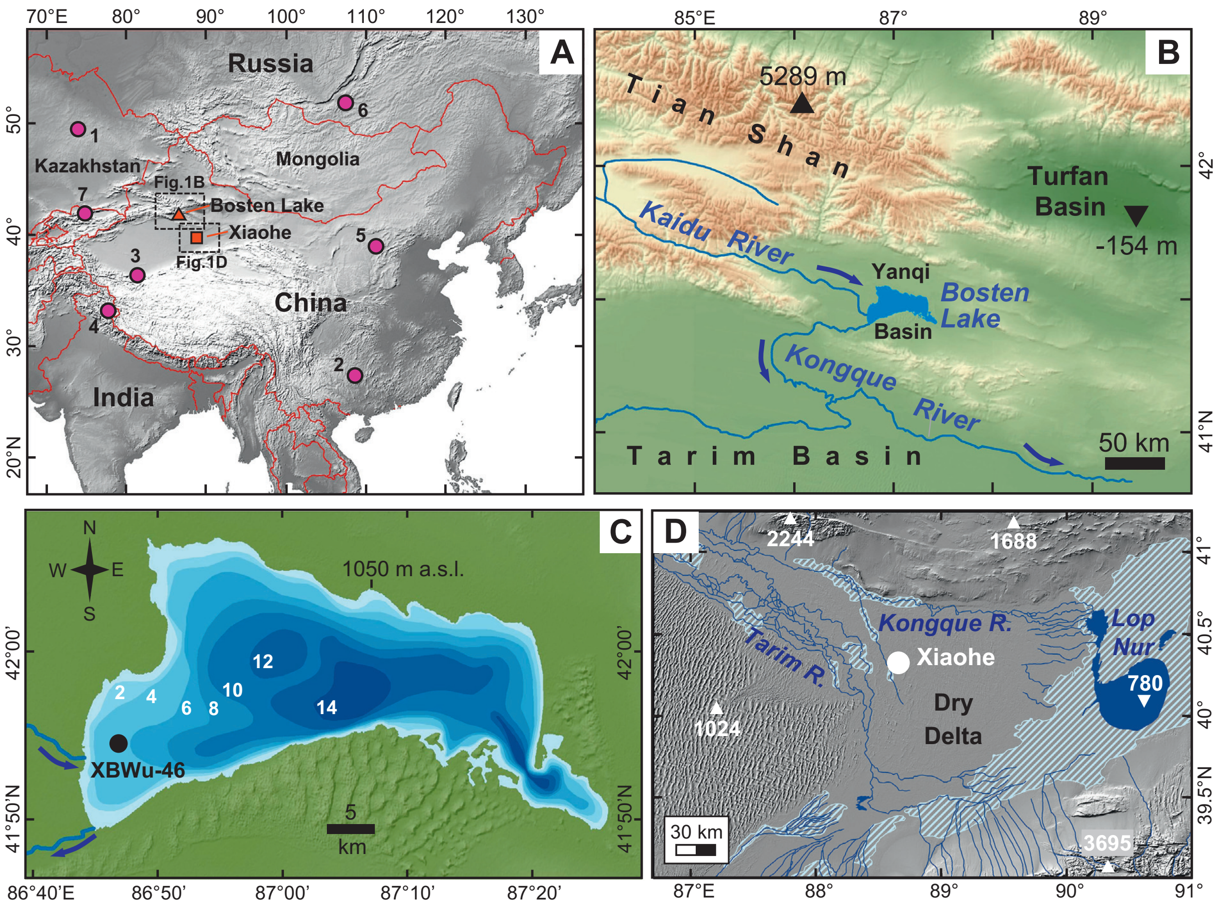

Fig. 1. Topographic maps showing (A) locations of Bosten Lake (red triangle) and its catchment area, the Xiaohe archaeological site (red square) and the Lop Nur Basin, and other archives from eastern Eurasia (circles) discussed in the current paper, including (1) Pashennoe Lake (Kremenetski et al., 1997), (2) Dongge Cave (Yuan et al., 2004), (3) Liushui archaeological site and loess section (Tang et al., 2013), (4) Tso Moriri (Leipe et al., 2014a), (5) Jinjie section (Anwar et al., 2018), (6) Burdukovo section (Kravchinsky et al., 2013), (7) Son Kul (Huang et al., 2014); (B) the Bosten Lake catchment area in the eastern Tian Shan (elevation based on Shuttle Radar Topography Mission (SRTM) V4.1 data (Jarvis et al., 2008) with color range from dark green to brown indicating lowest and highest elevation, respectively); (C) the Bosten Lake (1050 m a.s.l.) bathymetric map (white numbers show lake depth in m) with the XBWu-46 core location; and (D) location of the Xiaohe archaeological site and Lop Nur in the present-day desert area of the eastern Tarim Basin with white numbers (elevation in m a.s.l.) indicating prominent heights and depressions. Selected country names and modern political borders in (A) are shown for orientation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sets may involve decoupled, though, complementary signals, which integrate processes occurring in high and low altitude areas. Palynological analysis may help to decipher environmental drivers of signals from various proxies. Pollen analysis of the radiocarbon-dated bottom sediments from Bosten Lake was carried out in an unpublished PhD thesis (Huang, 2006); however, although, the entire pollen dataset is not yet published internationally in full, several selected proxies (i.e. the *Ephedra* percentage curve and the *Artemisia*/Chenopodiaceae (A/C) ratio) have been used (e.g. Huang et al., 2009) for reconstructing late-glacial and Holocene climate trends in arid Central Asia. Nonetheless, a detailed palynological investigation of the Bosten Lake sediments has not been published to date.

From arid Central Asia, numerous multi-proxy studies on the Holocene climate dynamics are already available (e.g. Chen et al., 2008; Huang et al., 2009; Rudaya et al., 2009; Zhao et al., 2009; Ran and Feng, 2013). These comprehensive studies represent a valuable contribution to the ongoing discussion on the temporal and spatial patterns of the Holocene moisture evolution in this environmentally vulnerable region, but also report some contradictory results and interpretations. Zhao et al. (2009) reconstructed a wet period occurring ca. 8500–5500 cal. yr BP at most sites from western Inner Mongolia to Xinjiang and a drying trend during the late Holocene. By contrast, other studies suggest for arid Central Asia a trend of increasing moisture since the end of the late-glacial period with the highest moisture level during the late Holocene (Chen et al., 2016; H. Long et al., 2017; Zhang et al., 2017). Huang et al. (2009), on the other hand, suggested that the regional climate in the Bosten Lake area was relatively dry between ca. 8000 and 6000 cal. yr BP and became more humid afterwards. Despite such differences, which require further investigations, all studies agree that the reconstructed spatial/temporal complexity of the Central Asian climate reflects large-scale interactions of competing factors, including the monsoon and westerly circulation systems and topographically-induced regional atmospheric dynamics (Chen et al., 2008; Rudaya et al., 2009; Zhao et al., 2009).

Humans could be another factor influencing the local and regional environments; however, the role of human (particularly agricultural) activities in the Holocene vegetation changes requires further investigation (Zhao et al., 2009). Despite a growing body of archaeological data, the timing and routes of agriculture dispersal in Xinjiang remain controversial. Long et al. (2018), using an extensive set of directly radiocarbon-dated crop remains from archaeological sites in northern China and a Bayesian modelling approach, suggested that wheat cultivation appeared in the Xinjiang region around 2100–1700 BCE (95% probability range). So far, the oldest direct evidence for crop cultivation (including wheat, barley, and millet) in Xinjiang are from the Xiaohe archaeological site (Fig. 1D). This ancient

cemetery with over 330 burials was first discovered by Sven Hedin's expedition in 1911 and re-visited by the Swedish archaeologist Folke Bergman, who investigated 12 burials in 1934 (Bergman, 1939). In 2002, the Relics and Archaeology Institute of Xinjiang Uygur Autonomous Region started a full-scale scientific investigation of the Xiaohe cemetery (Relics and Archaeology Institute, 2007), excavating about 170 graves and initiating a number of international research projects. Li et al. (2013a) analyzed samples of clay, which plastered four of the so-called "mud coffins" representing the oldest layer of the Xiaohe graves for pollen and plant macrofossils. However, the pollen recovery reported in their study was very poor and did not allow robust interpretation.

Aiming to promote a better understanding of regional palaeoenvironmental changes, the current paper presents new records of pollen and non-pollen palynomorphs (NPPs) from the reference sediment core XBWu-46 collected in the south-western part of Bosten Lake (Wünnemann et al., 2003, 2006). These proxy records are used to address several major issues discussed in the above-mentioned previous studies by reconstructing (i) changes in mountain forest and lowland steppe/desert vegetation reflecting regional climate (mainly moisture) conditions; (ii) limnic conditions and lake evolution; and (iii) past human activities and potential human impact on the regional vegetation and on the lake system. Additionally, we present new results of geochemical and pollen analyses of a radiocarbon-dated clay sample from the mud coffin BM28 in Xiaohe, which likely represents an initial stage of complex agro-pastoral economy in the region (Long et al., 2018) and complements the plant macrofossil analysis presented by Li et al. (2013a).

2. Regional setting

Bosten Lake (41°56′–42°14′N, 86°40′–87°26′E) is situated in the intra-mountain Yanqi Basin in the south-eastern part of the Tian Shan, Northwest China (Fig. 1). The lake has a maximum depth of 16 m, a mean depth of 8.8 m, a surface area of ca. 1000 km^2, and a catchment, which covers about 56,000 km^2. The lake is fed by precipitation and melt water run-off from the upper catchment area. The Kaidu River accounts for about 83% of the water inflow (Fu et al., 2013; Wei et al., 2002; Yang and Cui, 2005). The lake drains through a south-western outlet into the Kongque River, which ends in a depression formerly occupied by now desiccated Lake Lop Nur (also called Lop Nor).

The ancient cemetery Xiaohe is situated in a present-day desert, west of a vast dry basin formerly occupied by Lop Nur (Fig. 1D). The cemetery itself is a striking paradox. The absolute majority of deceased lies in the sand under boat coffins turned upside-down on a giant sand dune rising over the flat desert landscape. Much evidence, including the boat-shaped coffins covered with cattle skins, feathers of water-birds clung to scepters, flattened goose-quills forming the teeth of wooden masks, and numerous wooden poles made of poplar trees (*Populus euphratica* Oliv.) trunks (Li et al., 2013a), indicates a life among rivers and lakes, marshes and riparian forests. Indeed, the site is located in the huge delta area formed by the rivers Kongque and Tarim (Fig. 1D), and the dry valley of the Small River ('Xiaohe' in Chinese) – a former branch of the Kongque River – is about 4 km away from the cemetery (Li et al., 2013a).

The modern climate of Xinjiang is extremely continental, with cold winters, hot summers, and very low precipitation outside the high alpine areas. Arid and hyper-arid conditions in the Junggar Basin to the north and in the Tarim Basin to the south of Bosten Lake are caused by their position in the rain shadow of the Central Asian mountains, which almost entirely block moisture transport from the Atlantic Ocean (Domrös and Peng, 1988). In the eastern Tian Shan the northern slopes experience relatively humid conditions, while the southern slopes are relatively dry. The range of mean annual precipitation stretches from to 400–500 mm in the subalpine Tian Shan to only 70–80 mm per year in the Yanqi Basin (Fu et al., 2013; Yang and Cui, 2005; Zhang et al., 2004). Close to the lake the mean temperature is about 28 °C in July and −10 °C in January (Huang et al., 2009).

Altitudinal and latitudinal temperature and precipitation gradients in the eastern Tian Shan influence vegetation distribution. In the north moisture-demanding communities reach lower elevations than in the south (Zhang et al., 2004). Major vegetation belts include sparse subnival communities, high-alpine meadows, alpine steppe, subalpine spruce forests with *Picea schrenkiana* (mainly in the north), montane forest-steppe with *Betula*, steppe and desert communities (Fan and Du, 1999; Feng et al., 2006b; Wang, 1961; Zhang, 1992a, 1992b; Zhang et al., 2004). Reed meadows with *Phragmites* and *Typha* are widely distributed west of Bosten Lake, and halophytes occur at near-shore sites subject to strong evaporation (Chen et al., 2006a; Mischke and Wünnemann, 2006; Wei et al., 2002; Zhang et al., 2010; Zuo et al., 2007). Ruderal vegetation is common in inhabited areas, and manure of cultivated crops causes phosphorus eutrophication of the lake (Wünnemann et al., 2006; Zuo et al., 2007).

3. Material and methods

3.1. Sediment samples

Core XBWu-46 (41°56.9′N, 86°46.5′E) was retrieved at a water depth of 5.88 m ca. 6 km off the Kaidu River mouth (Fig. 1B and C). The 925-cm-long core comprises layers of organic-poor sand with some fine gravel (925–914 cm), fine-grained clayey and carbonate-rich sediments (914–15 cm) with two basal layers of peat (904–900 and 884–880 cm) and a layer with low organic content (600–405 cm), and a layer of dark-grey mud (15–0 cm). The fine-grained sediments show several layers with increased amounts of silt and sand (Mischke and Wünnemann, 2006; Wünnemann et al., 2003, 2006). Sub-sampling was performed by cutting all core segments into 1-cm-thick slices, which were used for different analyses. The pollen analysis presented in this paper was conducted on 50 samples, which allows an average temporal resolution of about 170 years.

While most of the coffins found in Xiaohe have a boat shape, a few rectangular coffins are completely plastered with clay. Li et al. (2013a) investigated samples of clay from four of these "mud coffins" for pollen and plant macrofossil analyses. However, the pollen recovery reported in their study was very poor. Therefore, a clay sample from the mud coffin BM28 representing the earliest burial layer of the Xiaohe cemetery was used in the present study for analyzing pollen and other microfossils. Additionally, basic geochemical parameters of this single sample such as TIC (total inorganic carbon), TOC (total organic carbon), and the main mineralogic components were determined by common analyses as described in Vogel et al. (2016).

3.2. Radiocarbon dating and chronological modelling

Five ^{14}C dates (Table 1) used for age control of the XBWu-46 sediment sequence were reported in Wünnemann et al. (2006). These dates

Table 1
AMS ^{14}C dates (Wünnemann et al., 2006) obtained from the XBWu 46 sediment sequence. Calibrated ages were obtained through the IntCal13 calibration curve (Reimer et al., 2013) using OxCal v.4.3 software package (Bronk Ramsey, 1995).

Laboratory code	Core depth (cm)	^{14}C date (^{14}C yr BP)	Calibrated 95% range (cal. yr BP)	Calibrated median (cal. yr BP)
KIA 13113	13–15	102 ± 24	263 to 23	110
KIA 13114	91–93	1207 ± 23	1226 to 1063	1128
KIA 13115	400–402	3866 ± 30	4413 to 4160	4300
KIA 13116	620–622	4949 ± 33	5737 to 5604	5673
KIA 13117	880–882	7368 ± 36	8318 to 8047	8188

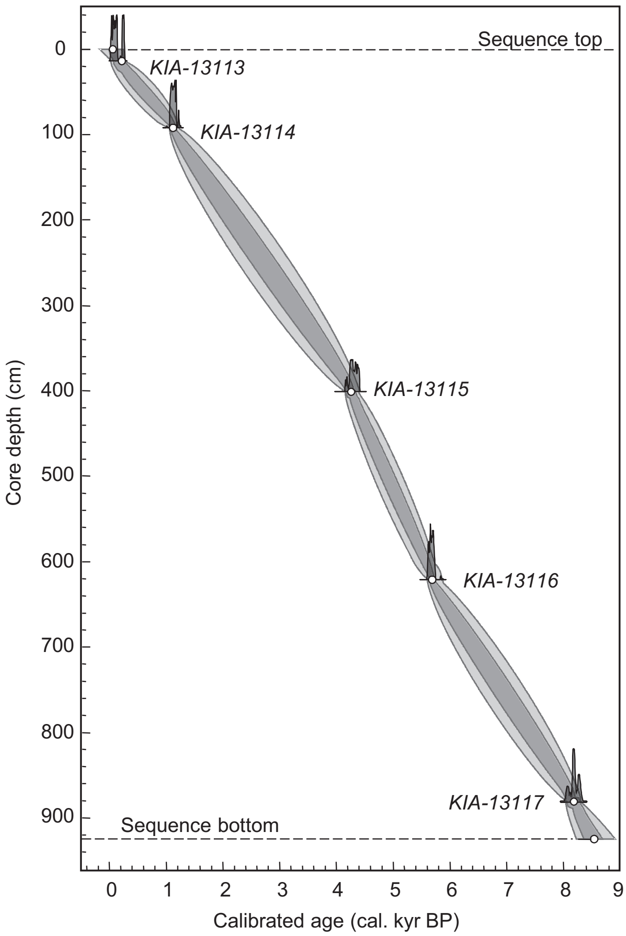

Fig. 2. Age-depth model (this study) applied to the XBWu-46 core pollen record (Fig. 4) presented here. Used calibrated radiocarbon datings (Table 1) are shown by their 95% confidence intervals (grey silhouettes), median ages (white dots), and lab numbers. The uppermost and lowermost white dots represent, respectively, the top and bottom of the XBWu-46 sediment sequence.

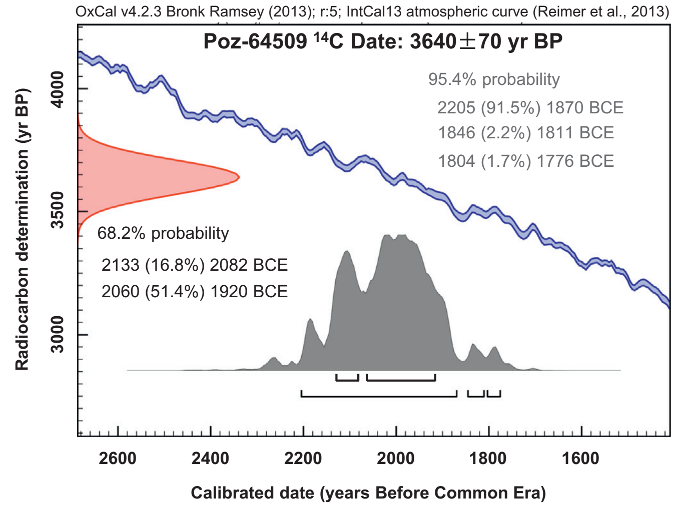

Fig. 3. Radiocarbon date and calibrated age of the clay sample from the BM28 coffin discussed in this study. The pink and grey curves show probability density distribution of, respectively, uncalibrated and calibrated ranges of the ^{14}C date. The 68% and 95% ranges are highlighted at the bottom of the calibrated distribution (grey curve). The blue curve is the IntCal13 calibration curve (Reimer et al., 2013). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

were based on terrestrial plant remains or sediment bulk organic fractions. In the current study, the five conventional ^{14}C ages were recalibrated with the IntCal13 calibration curve (Reimer et al., 2013) using the OxCal v.4.3 software package (Bronk Ramsey, 1995). We adopted a Poisson process depositional model (Bronk Ramsey, 2008) to establish the sequence's age-depth relationship (Fig. 2). The critical values for the agreement index and convergence index in the model were set to, respectively, 60% and 95% (Bronk Ramsey, 1995).

A bulk micro-sample of plant remains, possibly representing wheat and/or millet straw used to reinforce the mud for construction purposes (Li et al., 2013a), was recovered from the clay cover of the BM28 coffin and sent to the radiocarbon laboratory in Poznan for AMS age determination. The obtained radiocarbon date (Fig. 3) was converted into calendar age using the OxCal v.4.3 software package (Bronk Ramsey, 1995) and the IntCal13 calibration curve (Reimer et al., 2013).

3.3. Palynological analysis

Pollen and NPPs were extracted from the lake sediment samples applying hydrofluoric acid and acetolysis treatments and ultrasonic sieving through 7-μm meshes (Fægri and Iversen, 1989). One *Lycopodium* marker spore tablet (batch no. 938934: 1 tablet contains 10,679 ± 426 spores) was added to each sample for calculating absolute concentrations of palynomorphs (Maher, 1981; Stockmarr, 1971). Taxonomic determinations were performed using transmission light microscopy at magnifications of 400× and, in critical cases, 1000×. Counted sums generally exceed 500 terrestrial pollen grains per sample. Pollen and NPPs were generally well preserved and determined according to basic references (Jankovská and Komárek, 2000; Komárek and Jankovská, 2001; Moore et al., 1991; van Geel et al., 1989, 1996; Wang et al., 1997).

Pollen percentages for terrestrial taxa were calculated based on the terrestrial pollen sum taken as 100%. Percentages for limno- and telmatophyte plants and spore-producing plants were calculated based on the terrestrial pollen sum plus the sum of palynomorphs in the corresponding group. The pollen percentage diagram (Fig. 4) was drawn using Tilia software (Grimm, 1993, 2004) and subdivided into assemblage zones and subzones applying square-root transformation of percentage data and stratigraphically constrained cluster analysis by the method of incremental sum of squares (Grimm, 1987).

Pollen percentage ratios are frequently used as a semi-quantitative characteristic of regional past climate or environments (e.g. Fowell et al., 2003; Herzschuh et al., 2004; Leipe et al., 2014a). The ratio of *Artemisia* to Chenopodiaceae (A/C) has been used as an indicator of moisture availability in arid to semi-arid environments (El-Moslimany, 1990). In the dry regions of China, the A/C ratio estimates the contribution of relatively moist steppe vegetation with prevailing *Artemisia* in relation to Chenopodiaceae-dominated desert and halophyte communities (An et al., 2006; H. Feng et al., 2006; Herzschuh et al., 2004). Zhao et al. (2012) have reviewed application and limitations of the A/C pollen ratio in arid and semi-arid China. They concluded that variance in the A/C ratio can permit identification of modern vegetation types and that the A/C ratio generally has a positive relationship with annual precipitation. Following Luo et al. (2009), A/C values around 1 point to desert-steppe, while ratios below 0.5 indicate desert environments. However, soil salinity, vegetation community composition, human activity, and sample provenance (e.g. soil and lake sediments) will affect the values of the A/C ratio in different vegetation zones and therefore it can only be used to reconstruct vegetation types and climate change in regions with annual precipitation < 450–500 mm, and in steppe, steppe- desert, and desert areas (Zhao et al., 2012). Increased contribution of *Ephedra* (E) pollen has been considered as another indicator for dry steppe and desert conditions (Herzschuh et al., 2004; Huang et al., 2009; Luo et al., 2009; Prentice et al., 1996). However, understanding the environmental factors, which control the growth of

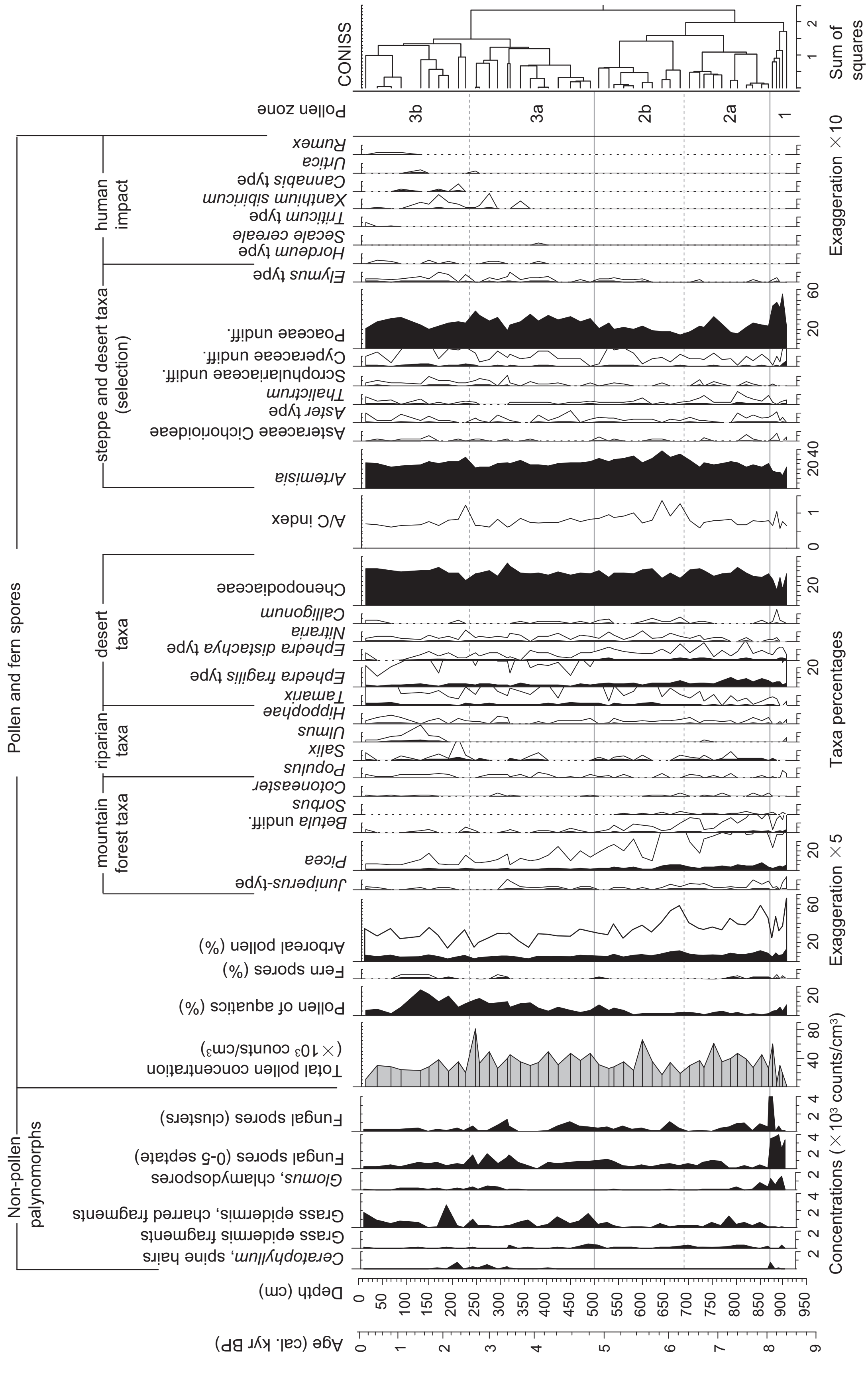

Fig. 4. Simplified diagram showing results of the palynological investigation of the XBWu-46 core from Bosten Lake.

Ephedra in the study area, needs more investigation. For example, we observed dense *Ephedra* shrub cover in the mountain valley next to the slope covered with low juniper shrubs. Neither vegetation nor climate of the valley could be ascribed as desert. A better knowledge on the *Ephedra* ecology is particularly important for interpretation of the *Ephedra* percentage curves (e.g. Huang et al., 2009 and this study) in the palynological records from the region. In the current study, the A/C index and the arboreal pollen (AP) percentage curve are used to discuss lower altitude desert/steppe and mountain forest development and to illustrate relationships between the regional climate and vegetation.

The clay sample representing the BM28 coffin from Xiaohe was chemically treated and microscopically analyzed in the same way as the Core XBWu-46 sediment from Bosten Lake. Due to low pollen concentration, pollen counting was stopped after identification of 300 pollen grains.

4. Results

4.1. Chronology

The established chronology shows no significant change in sedimentation rate (Fig. 2), which coincides with the fact that there are no significant variations in sediment composition (e.g. different particle sizes) throughout the core (Wünnemann et al., 2006). The 925-cm sediment sequence records a ca. 8500-year environmental history of the Bosten Lake region, starting from ca. 8540 cal. yr BP (median) at the bottom and ending at ca. 60 cal. yr BP (median) at the top. Our results confirm the XBWu-46 core age model, which was developed and discussed in detail by Wünnemann et al. (2006).

The result of radiocarbon dating of the short-lived terrestrial plant remains recovered from the clay sample from Xiaohe is shown in Fig. 3. The radiocarbon date 3640 ± 70 ^{14}C yr BP represents the interval 4155–3726 cal. yr BP (95.4% range) and 4083–3870 cal. yr BP (68.2% range), suggesting that the onset of burial activities (and probably the onset of human habitation) at the site goes back to at least four millennia ago. This approves an earlier estimation, which dated the lowest layer of the Xiaohe cemetery to 3980 ± 40 cal. yr BP (Li et al., 2010). Well-preserved wheat grains from the cemetery were dated to 3710–3380 cal. yr BP (Long et al., 2018) representing the final stage of cemetery use and most likely the end of the settlement.

4.2. Pollen assemblage zones of core XBWu-46

Results of the palynological analysis of core XBWu-46 are presented in Fig. 4. Three pollen assemblage zones (PAZ) and subzones (PASZ) were defined by splitting the CONISS-derived clusters at a total sum of squares of 2.0 and 1.45, respectively. Total pollen concentration is ca. 30,000–50,000 grains per cm^3 through most of the sequence. A few samples demonstrate higher values (ca. 60,000–80,000 grains per cm^3). Samples from the bottom sandy layer (below 912.5 cm) revealed very low pollen quantities and were therefore excluded from the percentage calculations. On the other hand, this core sequence revealed abundant grass epidermis fragments and fungal spores (Fig. 4).

4.3. Pollen assemblage and basic geochemical parameters of the BM28 clay sample from Xiaohe

Results of the geochemical analysis of the BM28 coffin clay sample show that the main component is quartz (SiO_2). The TIC content is 2.2% and the TOC content is 1.4%. The fine-grained, muddy character of the sample is due to relatively large proportions of the clay minerals illite and chlorite. A few tiny shells of ostracods (seed shrimps) also discovered in the clay sample (Fig. 5A) were identified as juveniles and one poorly preserved adult form of *Pseudocandona* sp.

Results of the palynological analysis of the BM28 sample are presented in Fig. 5B and Table 2. The total pollen concentration is also very low, i.e. 550 grains per gram of dry sediment. Altogether, 300 pollen grains assigned to 18 taxa plus another 27 poorly preserved herbaceous pollen grains assigned to *Indeterminata* were recovered from the sample allowing reliable calculation of pollen percentages. The pollen assemblage demonstrates absolute predominance of Poaceae (42.5%) and *Artemisia* (23.5%) pollen, followed by *Typha* (4.3%), Cyperaceae (4%), *Ephedra* (3.7%), and Chenopodiaceae (1.5%). The A/C ratio is 15.4 pointing to a moist steppe or meadow environment. This interpretation is supported by relatively high values of *Typha* (4.3%) and Cyperaceae (4%).

5. Interpretation and discussion

5.1. Vegetation development and regional climate dynamics

The pollen diagram of the XBWu-46 record (Fig. 4) reveals dominance of herbaceous taxa in the Bosten Lake sediment through the entire record. The most abundant taxa are Chenopodiaceae, *Artemisia*, and Poaceae representing desert, steppe, and coastal vegetation communities. The records of *Picea* (spruce) and *Betula* (birch) pollen demonstrate higher percentages in the lower part of the pollen diagram (zones 1 and 2) suggesting a wider distribution of subalpine mountain forests in the past, prior to ca. 4300 cal. yr BP (Fig. 4). Several pollen records from Xinjiang confirm a wider than present distribution of forests in the Tian Shan during ca. 8000–4300 cal. yr BP in correspondence to warmer and moister climatic conditions (Zhao et al., 2007). Today in the northern Tian Shan coniferous forests with *Picea schrenkiana* occur at altitudes of 1600–2800 m a.s.l., while in the south scattered stands of spruce are restricted to moister sites (mainly valleys) at elevations of 2000–2800 m a.s.l. (Feng et al., 2006b; Zhang et al., 2004).

Relatively high frequencies of *Picea* pollen were recorded in modern surface samples collected close to the western reed belt of Bosten Lake (Feng et al., 2006b; Huang et al., 2004; Zhou et al., 2001), reflecting significant water transport of spruce pollen (Wu et al., 2013) by the Kaidu River. The upper section of core XBWu-46 reveals, in turn, low abundances of spruce pollen (Fig. 4). These opposing results might be explained by a filtering effect of coastal reed vegetation, which stops significant parts of the river-transported sediment (probably including large pollen grains) from entering the lake. Thus, *Picea* pollen recorded in the lake sediment likely represent airborne pollen influx. Consequently, higher percentages of spruce pollen in the XBWu-46 record should predominantly reflect air transport from mountain forest, which occupied, under more humid climatic conditions, a larger area than today.

The gradual long-term trend towards decline of mountain forest vegetation and dominance of desert communities in lower elevated areas between 8500 and 4300 cal. yr BP expressed by the AP and A/C curves (Fig. 4) is superimposed by relatively short oscillations in the AP percentages curve (Fig. 6A), which may reflect changes in the regional precipitation and moisture availability. One of the major oscillations occurs near the base of the record (i.e. in PAZ 1). In the sediment column, it corresponds to intermittent peaty layers, suggesting a relatively low lake level and a dry climate. Previous reconstructions from Bosten Lake ascribed it as a regional evidence of the broadly-recognized cold event around 8200 cal. yr BP that originated in the North Atlantic (Mischke and Wünnemann, 2006; Wünnemann et al., 2006; Zhang et al., 2010).

The interval between 8050 and 5350 cal. yr BP shows higher than average AP percentages (Fig. 6A), suggesting moisture conditions generally favorable for the regional mountain forest vegetation. By contrast, the XBWu-46 aquatic pollen record (Fig. 6B) demonstrates lowest percentages during this time interval, indicating relatively high river water inflow, which contributed to a rise in lake level, in line with the other proxies from Bosten Lake used to reconstruct the lake status (Wünnemann et al., 2006; Fig. 6C). The AP percentages (Fig. 6A) show

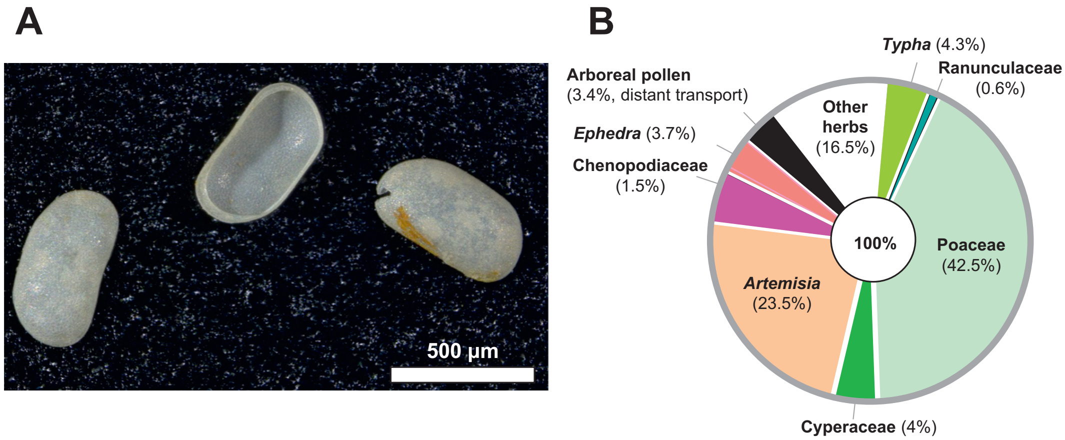

Fig. 5. (A) Photos of the ostracod valves recovered from the clay sample from the BM28 mud coffin discussed in this study. (B) Simplified pollen composition and taxa percentages of the same sample.

Table 2
Results of the pollen analysis of the clay sample from the mud coffin BM28.

Pollen taxon	Counts	Percent
Alnus sp.	1	0.3
Betula sp.	4	1.2
Pinus Haploxylon type	3	0.9
Pinus sp.	3	0.9
Ephedra distachya type	2	0.6
Ephedra fragilis type	10	3.1
Poaceae	139	42.5
Cyperaceae	13	4.0
Artemisia	77	23.5
Asteraceae Asteroideae	3	0.9
Asteraceae *Senecio* type	2	0.6
Asteraceae Cichorioideae	18	5.5
Brassicaceae	1	0.3
Chenopodiaceae	5	1.5
Ranunculaceae	2	0.6
Rosaceae	1	0.3
Saxifragaceae	2	0.6
Typha	14	4.3
Indeterminata	27	8.3
Total sum	**327**	**100**

further decrease after 5350 cal. yr BP and reach minimum values between 4000 and 2000 cal. yr BP. These changes possibly reflect a decrease in the distribution area of trees and shrubs due to decreased precipitation in the mountains. The decreased moisture availability in the upper catchment corroborates progressive increase in the aquatic pollen percentages between 5300 and 1500 cal. yr BP (Fig. 6B), suggesting spread of aquatic vegetation and shallower lake environments (Fig. 6C). Slightly higher AP percentages are registered after 2000 cal. yr BP (Fig. 6A), possibly reflecting slight improvement of the mountain climate and regional water balance. Such interpretation is supported by a distinct drop in the aquatic pollen percentages after 1500 cal. yr BP (Fig. 6B) and a higher lake status reconstructed for the last millennium (Fig. 6C).

In contrast to the dynamically changing moisture conditions at higher altitudes, the A/C index (Fig. 4) representing low-altitude Yanqi Basin vegetation shows relatively low (i.e. desert) values through the entire XBWu-46 record, interrupted by four short-term peaks towards desert-steppe environments at around 8200, 6200, 5900, and 2500 cal. yr BP. This indicates rather stable desert environments with a strong presence of Chenopodiaceae and *Ephedra* in the Yanqi Basin vegetation during the past 8500 years.

Contrasting moisture conditions at low and high altitudes can be explained by features of the regional climate complicated by effects of topography. The interplay of the major circulation systems (i.e. the Atlantic westerlies and the Asian summer monsoon) responsible for the moisture transport to Central Asia are frequently involved in the discussion and interpretations of environmental proxies (Wünnemann et al., 2006; Zhang et al., 2010; Rudaya et al., 2009; Kleinen et al., 2011). Climate reconstructions derived from lacustrine pollen records from the Himalaya (Fig. 6H) demonstrate that both the westerlies and the summer monsoon have been transporting precipitation to the higher altitudes during the Holocene period, though their contribution to the regional water budget has been variable over time (Leipe et al., 2014a, 2014b; Demske et al., 2016).

Our pollen record from Bosten Lake (Fig. 4) suggests that zonal desert vegetation in the low-elevated Yanqi Basin (and probably, in the entire Tarim Basin) outside the mountain river valleys or lake shores remained insensitive to the precipitation variations at high altitudes due to the arid climate characterized by extremely high potential evaporation greatly exceeding actual precipitation elsewhere outside the high mountains.

The A/C ratio of the BM28 clay sample is 15.4 and points to a moister (i.e. steppe or meadow) environment which existed in this area (that is currently a desert) ca. 4000 years ago. Statistical analysis of recent pollen spectra from different vegetation types in arid and semi-arid China shows that A/C ratios may reach up to 33.33 in the steppe and up to 23.09 in the desert steppe regions (Zhao et al., 2012).

Former moist sedimentation environments and the aquatic origin of the clay sample are supported by the TIC data that represents mainly calcite ($CaCO_3$) and a minor portion of dolomite ($CaMg(CO_3)_2$). Sediment geochemistry and ostracod (Fig. 5A) records suggest that accumulation likely occurred during the spring/early summer or autumn period within freshwater (salt content < 2 g per liter and traces of gypsum ($CaSO_4 * 2(H_2O)$) identified by the geochemical analysis) and relatively quiet aquatic (i.e. lacustrine) environments (S. Mischke, personal communication).

Relatively high percentages of *Typha* and Cyperaceae pollen (Fig. 5B), representing coastal aquatic vegetation communities, together with relatively high percentages of *Ephedra*, representative of desert environments, indicate the mixed character of the pollen assemblage and thus a mixed vegetation, which contributed pollen to the clay sample. Indeed, one half of the pollen (e.g. Poaceae, Cyperaceae, *Typha*) represents local, mesic vegetation communities growing at lake or river shores, while the other half of the spectrum is more typical for arid steppes and deserts representing regional vegetation.

Various proxy-based reconstructions (e.g. Leipe et al., 2014a; Ran and Feng, 2013; Rudaya et al., 2009) and model-based simulations of the Holocene climate and vegetation (e.g. Kleinen et al., 2011) indicate that absolute values and relative contribution of the westerlies and summer monsoon to the regional moisture budget varied greatly, both

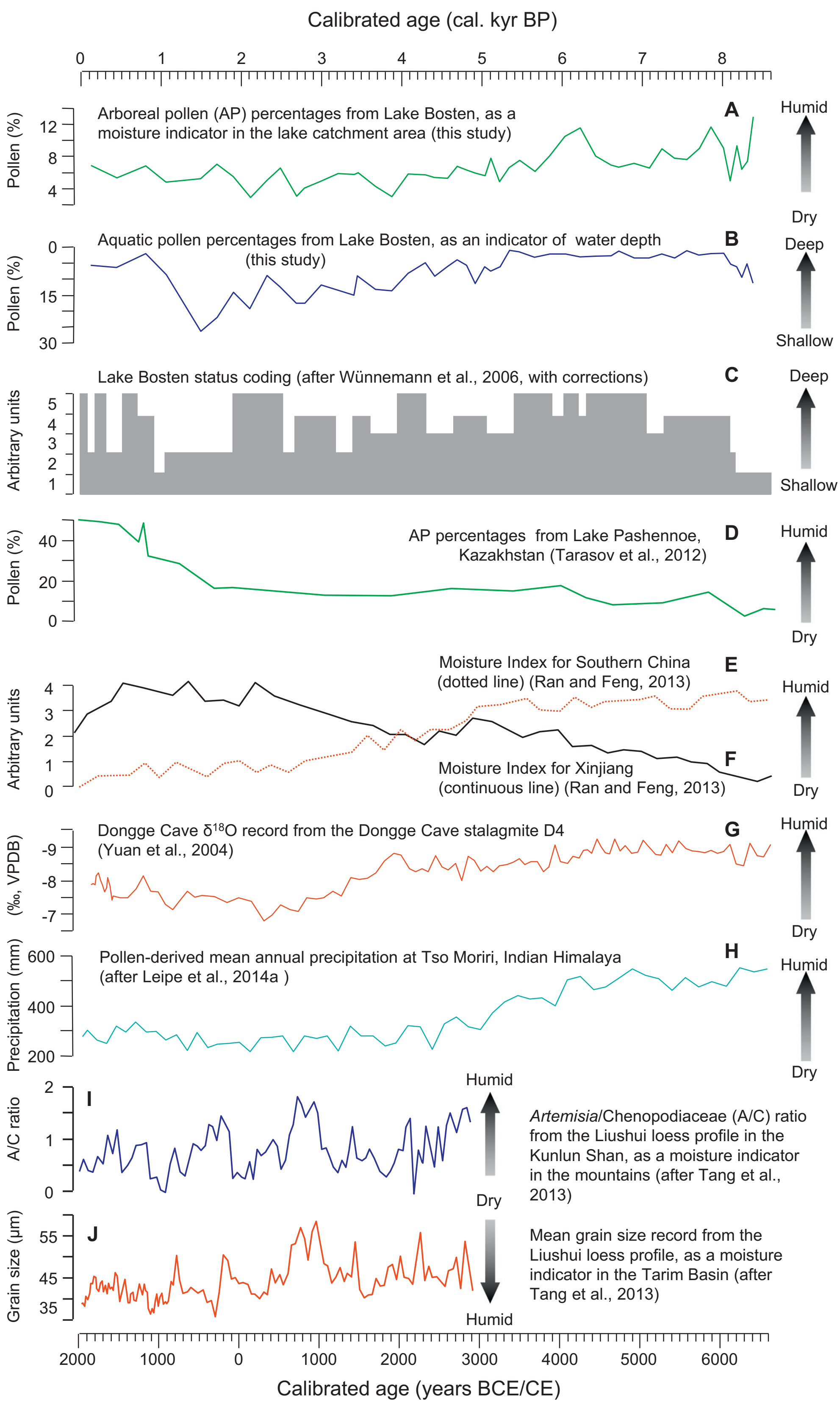

Fig. 6. Selected results of this study highlighting the past climate changes in the Bosten Lake catchment area along with published proxy records discussed in the text. Locations of the records are given in Fig. 1. The graphs demonstrate: (A) – changes in arboreal pollen (AP) and (B) in aquatic pollen percentages from Bosten Lake (this study); (C) – changes in the reconstructed lake status/relative water depth of Bosten Lake (after Wünnemann et al., 2006); (D) – AP percentages from Lake Pashennoe, Kazakhstan (after Tarasov et al., 2012); (E) – the regionally-averaged moisture index for the south-eastern China region and (F) for the Xinjiang region (after Ran and Feng, 2013); (G) – oxygen isotope record from the Dongge Cave stalagmite D4 (after Yuan et al., 2004); (H) – pollen-based annual precipitation reconstruction from Tso Moriri (after Leipe et al., 2014a); (I) – *Artemisia*/Chenopodiaceae (A/C) ratio and (J) – mean grain size record from the Liushui loess profile in the Kunlun Shan (after Tang et al., 2013).

temporally and spatially across Central Asia. Therefore, the onset, magnitude, and length of the Holocene climatic (i.e. moisture/temperature) optimum in different regions of Asia are among the frequently discussed questions (Leipe et al., 2014a; Rudaya et al., 2009; Stebich et al., 2015; Wang et al., 2005; Zhou et al., 2004; Zhou et al., 2016). The ongoing debates remain hot, particularly regarding the arid regions of north-western China, which are, for an objective reason, still poorly covered by good-quality proxy records.

Regionally-averaged moisture indexes demonstrate clearly opposite trends for the south-eastern and north-western parts of China (Ran and

Feng, 2013). For south-eastern China (Fig. 6E), where climate and annual moisture balance are controlled by the summer monsoon (Fig. 6G; Yuan et al., 2004), a pronounced early to middle Holocene moisture optimum prior to 5000 cal. yr BP and a subsequent gradual decline were reconstructed (Ran and Feng, 2013; Stebich et al., 2015). By contrast, the reconstruction performed for the Xinjiang region in north-western China reveals a low but growing moisture index between 8500 and 5000 cal. yr BP, a minor decline between 5000 and 4200 cal. yr BP, and a moisture optimum between 2200 and 500 cal. yr BP (Fig. 6F). Based on these differences between the regions, Ran and Feng (2013) suggest that the winter temperature variations in the North Atlantic region and the Atlantic westerlies were the major factors controlling the Holocene moisture variations in Xinjiang, while the summer monsoon did not play a significant role there. However, this interpretation is not in agreement with the results presented in the current study. In fact, the key moisture indicators in the Bosten Lake catchment area, such as the AP percentage curve (Fig. 6A), the pollen percentages of aquatic vegetation (Fig. 6B), and the lake status reconstruction (Fig. 6C) resemble the summer monsoon intensity isotope record from Dongge Cave (Fig. 6G) and, to a large extent, the moisture index curve from the monsoon-controlled regions of China (Fig. 6E). On the other hand, comparison to the moisture reconstruction for Xinjiang (Fig. 6F) proposed by Ran and Feng (2013) and for the westerly-controlled forest-steppe region of Kazakhstan (Fig. 6D) by Tarasov et al. (2012) (see also Kremenetski et al., 1997 for a detailed pollen record from Lake Pashennoe and four other sites) does not show such similarity, suggesting that the North Atlantic air masses started to play a more significant role in the moisture balance of the Bosten Lake catchment area only since about 1500 cal. yr BP.

The records from the neighboring areas of Kazakhstan, Mongolia, and Russia (Rudaya et al., 2009; Tarasov et al., 2012), situated west and north of Bosten Lake, demonstrate spatially and temporally different Holocene vegetation and climate histories, indicating that the westerly-associated moisture transport played an important role in the environmental dynamics of the regions situated west and north of the Altai and Tian Shan Mountains during the middle and late Holocene. By contrast, the moisture transport associated with the stronger-than-present summer monsoon was of pivotal importance for the environments of eastern Central Asia represented by the Bosten Lake study region during the early and middle Holocene.

A high resolution petromagnetic analysis of the Jinjie loess-paleosol sequence (5 in Fig. 1A) from the desert part of the Chinese Loess Plateau helps to reconstruct three warm-humid intervals (ca. 8400–3700, ca. 2400–1200, and ca. 810–480 cal. yr BP) during the Holocene (Anwar et al., 2018). The early phase of a substantial paleosol development indicates the middle Holocene climatic optimum associated with a stronger summer monsoon. The two younger (and less pronounced) phases of climate amelioration, however, cannot be traced in the records from monsoonal China (e.g. Fig. 6E), but corroborate the late Holocene moisture increase reconstructed for Xinjiang (e.g. Fig. 6F). This similarity between the Bosten Lake records presented in Fig. 6A–C and the reconstruction derived from the desert area of the Chinese Loess Plateau (Anwar et al., 2018) suggests that increased moisture levels in both regions were controlled by enhanced westerly-controlled precipitation.

The question about the moisture evolution and climate development in arid Central Asia caused a sharp controversy and hot scientific polemic during the past hundred years (e.g. Boomer et al., 2000). For example, G.Ye. Grumm-Grzhimailo, N.V. Pavlov, V.A. Smirnov, V.M. Sinitsyn, and A.V. Shnitnikov advocated for a drying trend during the historical period, while L.S. Berg, K. K. Markov, and some others argued against this hypothesis (Gumilyov and Aleksin, 1963). Debates have been ongoing into the current decade, with new results highlighting the spatial/temporal complexity of the environmental dynamics in Central Asia and warning against over-simplified conclusions and interpretations (see discussions in Morrill et al., 2003; Tarasov and Wagner, 2015).

The Bosten Lake sedimentary archive does not represent the only example of controversial interpretations. Mathis et al. (2014) presented a pollen study conducted on the middle Holocene (ca. 8350–2000 cal. yr BP) sediments from the high-altitude lake Son Kul (7 in Fig. 1A) in the central Tian Shan (Kyrgyzstan). Their reconstruction of vegetation and climate dynamics suggests that warmer/moister climate conditions occurred between 8350 and 5000–4500 cal. yr BP and more continental and arid conditions prevailed after 4500 cal. BP. The authors proposed that regional rainfall in the central Tien Shan and western Central Asia is likely to be predominantly controlled by the Eastern Mediterranean cyclonic system, referring to the close correspondence between climate archives of Son Kul and the Eastern Mediterranean and Caspian Sea regions, on one hand, and from the Xinjiang region, on the other hand. A multi-proxy study on the Son Kul sediment core (Huang et al., 2014), including grain size, magnetic susceptibility, sediment geochemistry, and isotope analyses on bulk and biogenic materials, helped to recognize that the long-term negative hydrological balance was interrupted by several short stages with marked increase of precipitation (e.g. 8300–8200, 6900–6700, 6300–6100, 5500–5400, 5300–5200, and 3100–3000 cal. yr BP), which also imply that moisture sources could have changed during the Holocene. Another research team working on the same lake used diatom, ostracod, sedimentological, geochemical, and stable isotope analyses on a ca. 6000-year-old lake sediment core to reconstruct shifts in water balance (Schwarz et al., 2017). In addition to an alternative name (i.e. Son Kol), their study provided an alternative interpretation of the lake history suggesting a closed basin lake/dry climate ca. 6000–3800 and ca. 3250–1950 cal. yr BP and an open lake/wet climate at 3800 and after 1950 cal. yr BP. A complex interplay of the driving factors was suggested to explain these regime shifts, including changing intensity and position of the westerlies and the Siberian Anticyclone that triggered changes in the amount of winter precipitation (Schwarz et al., 2017). In line with the Bosten Lake studies, these publications emphasize the importance of multi-proxy approaches to identify triggers, thresholds, and cascades of aquatic ecosystem transformations and pinpoint a necessity for regional climate modelling experiments to explore the effect of Eurasian atmospheric circulation patterns on the Holocene climate variability in Central Asia.

5.2. Vegetation development and human impact in the Bosten Lake pollen record

The decline of arboreal pollen in the Bosten Lake sedimentary record, particularly after 5000 cal. yr BP likely reflects a reduction of the forest vegetation in the catchment area. The decreasing trend in the AP curve (Fig. 6A) coincides with other evidence of decreasing moisture availability (Fig. 6B and C), suggesting that a progressive aridification of the regional climate probably played an important role in the vegetation changes recorded in the pollen diagram (Fig. 4). However, exploitation of wood resources by prehistoric human populations, as another possible reason for the forest decline, cannot be ruled out (Ren, 2000; Ren and Beug, 1999). Increased frequencies of charred grass fragments (Fig. 4), particularly since ca. 5000 cal. yr BP, might indicate fires caused by human activities. Archaeological data from Xinjiang (Hosner et al., 2016) demonstrate an increase in archaeological site numbers from 44 sites assigned to the period between 9000 and 4000 cal. yr BP to 153 sites assigned to the interval between 4000 and 2000 cal. yr BP.

Concerning the region around Bosten Lake, however, archaeological evidence of early habitation is scarce. Charred *Picea* wood fragments from the Yuergou tombs in the nearby Turfan Basin indicate use of spruce by the people living there between 2400 and 2300 cal. yr BP (Jiang et al., 2013). Another famous prehistoric archaeological site of the region – the Yanghai graveyard located in a present-day gravel desert (Beck et al., 2014; Jiang et al., 2006; Kramell et al., 2014) about

43 km southeast of the modern city of Turfan – reveals > 500 excavated tombs (Jiang et al., 2009) and a long period of use, suggesting substantial increase in human population and intensified human activities in the region between ca. 3100 and 1800 cal. yr BP (Beck et al., 2014).

Pollen indicators from Bosten Lake (Fig. 4) suggest a weak anthropogenic impact after 4350 cal. yr BP corresponding to generally low abundances of charred grass remains between 4350 and 2400 cal. yr BP. Evidence of cultivation comprises individual pollen grains of *Cerealia* type registered four millennia ago. This date corroborates the earliest finds of wheat and barley agriculture in Xinjiang associated with the Xiaohe graveyard (Fig. 1D; Long et al., 2018; Mallory and Mair, 2008). Because of overlapping morphological characteristics in cereal and wild grass pollen (Beug, 2004; Faegri and Iversen, 1989; Moore et al., 1991) the record of large Poaceae grains (> 37 μm) with thick non-cereal anuli assigned to *Elymus* type (Fig. 4) could also represent wild grasses growing in dry sandy places.

Further evidence of human activities inferred from the pollen record (Fig. 4) includes appearance of *Xanthium* (cocklebur) (after 3700 cal. yr BP) and *Cannabis* type (after 2500 cal. yr BP) pollen. Contemporaneous archaeological sites near Bosten Lake comprise the sedentary Xintala (Yengidala) Culture site dated to 1700–1400 BCE, with evidence for the cultivation of wheat and millet, and the Chawuhu (Charwighul) Culture site located north of the lake in the Tian Shan dated to 1000–400 BCE, which both can be related to the Andronovo Culture (Zhang, 2009). The initial spread of *Xanthium* near Bosten Lake precedes archaeological evidence from the Yuergou tomb site in the Turfan Basin, where numerous fruits and spikelets of *Xanthium strumarium* were discovered (Jiang et al., 2013). Continuous presence of *Xanthium* between 3100 and 1400 cal. yr BP at Bosten Lake covers the period of the Subeixi Culture related to the historical Cheshi State people (Li et al., 2013b), who cultivated cereals and hemp and collected *Xanthium* for unknown purpose (Jiang et al., 2013).

In sedimentary records from northern China, pollen of *Xanthium* is commonly regarded as a human activity indicator (Makohonienko et al., 2008). This genus grows in segetal and ruderal habitats (e.g. roadsides and riverbanks) and is classified primarily as a weed of cultivated fields (Zhang and Hirota, 2000). In the past, the cocklebur was utilized in China as a leafy vegetable and it was intentionally planted (Li, 1969). Similarly, the record of *Cannabis* type pollen at Bosten Lake corresponds to fossil seeds (*Cannabis* cf. *indica*) recovered from the Yanghai tombs, which were dated to ca. 2700 cal. yr BP (Jiang et al., 2006).

Appearance of these anthropogenic indicators in the Bosten Lake pollen record can be linked not only to local populations of the Xintala and Chawuhu Cultures, but also to agro-pastoral populations from the Turfan Basin (Beck et al., 2014; Jiang et al., 2013), as well as likely from other even more distant regions of Asia (Spengler et al., 2016). In particular, moister regional environmental conditions in western Central Asia after 5000 cal. yr BP may have increased the appeal of adopting an agricultural component into the economy of local groups and inspired them for searching new lands suitable for agriculture further east (Long et al., 2018; Spengler et al., 2016). It is easy to imagine that Bosten Lake and the catchments of the Kaidu and Kongque rivers offered very suitable environments for these agro-pastoralists coming from the west. It could have been also a desirable refuge for agro-pastoral tribes living in the arid and generally more challenging environments along the Tarim River and its tributaries (e.g. in Xiaohe, Fig. 1D), as soon as increasing aridity and unstable river water supply threatened their livelihood and shoved the inhabitants of the desert oases towards the mountains (Wagner et al., 2011).

Ancient populations in the Lop Nur area southeast of Bosten Lake are represented by the Xiaohe and Gumugou cemeteries dated to ca. 4100–3500 cal. yr BP (Long et al., 2018; Tang et al., 2013). Archaeological materials (e.g. Mair, 2006; Relics and Archaeology Institute, 2007) demonstrate that these people possessed a mixed agro-pastoral economy (i.e. grazing cows and sheep, growing wheat, barley, and millet) supplemented by hunting and fishing. Such way of life in the extreme arid environments of Xinjiang is only possible with a stable water supply provided by traversing rivers and permanent lakes or with a very sophisticated and reliable irrigation system (i.e. historical *karez*). Both archaeological and environmental data suggest that water supply was sufficient to support various human activities and riparian forest vegetation along the river valleys in the area between Bosten Lake and the terminal lake Lop Nur. Extensive use of wood seen in the Xiaohe cemetery also indicates that the past human population significantly impacted on local vegetation, which could have (together with worsening climate conditions) destabilized the fragile sustainability of the natural system around them during a relatively short time interval of about five centuries. After that they were forced to find other habitats and adapt their lifestyle to new environments (Wagner et al., 2011).

Higher abundances of *Xanthium* pollen and charred grass fragments recorded between 2200 and 1800 cal. yr BP (Fig. 4) indicate further intensified human activities in the region in line with archaeological records (Hosner et al., 2016). During the Han dynasty (206 BCE–220 CE) the Silk Road network became an increasingly important east-west trade connection through the Tarim Basin including the northern route across the Bosten Lake area. Since ca. 1200 cal. yr BP, *Triticum* and *Rumex* pollen as well as charred grass fragments point to the development of local settlements and an increasing anthropogenic impact on the regional vegetation as well as on the limnic system of Bosten Lake.

5.3. Environmental and archaeological records from the study region during the 2nd and 1st millennium BCE

In China, the interval between 4500 and 2000 cal. yr BP is in focus of many archaeological and palaeoenvironmental projects. It is particularly noted for its major cultural and environmental changes (Hosner et al., 2016; Long et al., 2018; Wagner et al., 2013), including a major weakening of the Asian summer monsoon (e.g. Fig. 6E and G), strengthening of the mid-latitude westerly flow (Fig. 6D and F), intensified west-east contacts and cultural exchanges, including spread of bronze metallurgy and wheat agriculture from western Central Asia to eastern Asia (Long et al., 2018; Tang et al., 2013), appearance of elites and central state formation (Liu and Chen, 2012; Wagner and Tarasov, 2014), and development of the mounted pastoral economy in the northern and western regions (Long et al., 2018; Wagner et al., 2011). The multidisciplinary 'Silk Road Fashion' project (e.g. Beck et al., 2014; Kramell et al., 2014; Schröder et al., 2016) reported, among other findings, the invention of trousers in the late second millennium BCE Turfan Basin and its likely affiliation with horseback riding and increased mobility.

The selection of environmental records from Bosten Lake (Fig. 6A–C) and other regions of Asia (Fig. 6D–H) clearly demonstrates the transitional character of the interval between 4000 and 2000 cal. yr BP both in the eastern (i.e. monsoon-controlled) and in the western (i.e. westerly-controlled) part of Asia. The trends in the moisture changes recorded in both regions are opposite, however. While the eastern part of Asia (including China and northern India; Fig. 6G and H) experienced decreasing moisture supply due to weakening of the summer monsoon, the western part (Kazakhstan and South Siberia; Fig. 6D) prospered from the strengthening of the westerly-related moisture transport through the middle latitudes and lower evaporation losses (Kleinen et al., 2011; Rudaya et al., 2009). The Xinjiang region, situated in the transitional zone between the two major atmospheric circulation systems, thus became an epicenter of the turbulent changes recorded in the environmental and archaeological archives. Its complex topography superimposed the large scale climate changes, making their effects stronger or milder and resulting in locally variable environments, even within relatively short distances as, for example, suggested by the different signals shown by the A/C (Fig. 4) and AP (Fig. 6A) records from Bosten Lake and by the A/C (Fig. 6I) and grain

size (Fig. 6J) records from the Liushui loess profile in the Kunlun Mountains (Fig. 1A) representing opposite trends in moisture development along the altitudinal gradient at multi-decadal/centennial scale (Tang et al., 2013). Kravchinsky et al. (2013) also demonstrated that Central Asian loess sediments well reflect large-scale climate variability. Multi-decadal peaks in the grain size record from their Burdukovo loess-soil section analysis (6 in Fig. 1A) resemble closely the Liushui record (even considering possible age confidence interval variations) and may indicate a rather global tendency than purely a regional interplay.

The combined use of high-resolution palaeoenvironmental and archaeological records (e.g. Leipe et al., 2014a, 2018) and robust chronological modelling (e.g. T. Long et al., 2017, 2018) will definitively help in getting more accurate reconstructions that allow for more reliable interpretations of complex human-environment interactions in the study region and to avoid over-simplistic and deterministic models.

6. Conclusions

- The fossil pollen record from core XBWu-46 (ca. 8540–60 cal. yr BP) contains two main environmental signals represented (i) by the AP percentages reflecting changes in the mountain and riparian forests and (ii) by the A/C pollen ratio reflecting variations in lowland desert vegetation around Bosten Lake.
- During the early and middle Holocene, the moisture budget of the study region was mainly controlled by the interplay of declining Asian summer monsoon precipitation in the south-eastern Tian Shan and higher-than-present Northern Hemispheric summer insolation.
- During the late Holocene (after ca. 2000 cal. yr BP) the hydrology of eastern Central Asia was mainly controlled by increasing precipitation linked to enhanced westerly disturbances, while influence of the strongly weakened Asian summer monsoon was insignificant or absent.
- The onset of human activities around Bosten Lake dates to 4000–3700 cal. yr BP and is likely related to early agro-pastoral groups, which probably originated from more distant western Central Asia regions. Human impact increased ca. 2200–1800 cal. yr BP due to intensified trade along the Silk Road during the Han dynasty (206 BCE–220 CE).
- Our findings underline the complex linkage between the recorded dynamic human activities and changing environmental conditions in eastern Central Asia, which manifests the need for interdisciplinary research projects to improve our understanding of past regional human–environment interactions.

Data availability

Datasets related to this article can be found online in the Open Access information system PANGAEA at https://doi.pangaea.de/10.1594/PANGAEA.896290.

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